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Combined power supply of decentralized energy consumers in conditions of extreme continental climate

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Abstract

In recent years, Kazakhstan has a growing interest in sustainable and energy effective combined supply for decentralized energy consumers. This is due to the development of the regions and the desire of consumers to obtain modern energy services.
This paper presents a comparative analysis of the energy efficiency of a combined energy autonomous system constructed on the basis of cogeneration (CHP) and trigeneration (TG) (involving low-potential heat of the earth (LPH)) low and domestic size power plants.
Method of the research is mathematical modeling and simulation of combined heating, cooling and power supplying in the system that combines a thermodynamic cycle in the internal combustion engine (ICE) and a geothermal heat pump with direct mechanical drive compressors (DMGHP).
Parametric adjustment and calibration of mathematical models are implemented on the basis of experimental research on a prototype for a trigeneration plant.
The research has established that the application of cogeneration plants for autonomous objects in extreme continental climate in Kazakhstan with a large seasonal variation in outdoor temperatures are significantly inferior to the energy efficiency of trigeneration plants. Thus, if the average annual energy efficiency of cogeneration systems based on internal combustion engines does not exceed 50–60 %, and the usage of TGP, which includes (DMGHP), allows to reduce the consumption of fossil fuel 3–4 times by involving source of renewable energy low-potential heat of the earth. It should be noted, that LPH is available in all regions of Kazakhstan and practically does not depend from climate conditions.

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Keywords: energy efficiency; cogeneration plant; trigeneration plant; geothermal heat pump; experimental research of prototype trigeneration plant

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1. Introduction

Kazakhstan ranks number nine in the world by area, but its population density is one of the lowest. Climatic conditions vary greatly over the Republic with hot dry summers in the south with temperatures reaching 45 °C and cold, long winters in the northern and eastern regions, where the temperature drops below -50 °C. Such conditions impose special requirements on the quality and reliability of energy supply. The provision of power and improvements to existing power supplies to the remote rural areas of Kazakhstan, is therefore an urgent task and is the focus of a number of key medium- and long-term government programs.

Currently, in the absence of centralized power, the electrical energy supply is usually provided by generating plants based on diesel (or gas piston) engines solely generating electrical power (monogeneration). The energy efficiency of such systems typically does not exceed 30 %. Heating on the other hand is mainly provided by furnace combustion of solid fuels with energy efficiency in the 50–70 % range.

Significant progress can be anticipated from the adoption of cogeneration systems which utilize the heat produced by internal combustion engines for heating purposes [1, 2].

Energy efficiencies of 80–85 % can be achieved by cogeneration plants feeding electrical and heating loads. With systems based on gas piston or diesel engines, the maximum energy efficiency is achieved at an approximate ratio of electrical to thermal generation of 40/60. Obviously, for housing and public utilities such a ratio will only be used over short periods in spring and autumn. As a consequence, the average overall annual efficiency of operating such cogeneration systems under the sharply varying continental climate in Kazakhstan will not exceed 50–60 %.

Since the 1950s, the application of geothermal heat pump (GHP) technologies for heating and cooling has progressed rapidly [3–7].

Despite its advantages, GHP is not widely used in Kazakhstan due to the high cost of imported equipment, the inevitable increase in electrical energy consumption and a lack of sufficient infrastructure to support design, installation and service organizations.

The aim of this work is to create a new generation of power generation equipment to provide autonomous energy supplies at remote sites, to enhance industrial production and widespread use of this technology throughout the country.

Based on the analysis of the latest achievements in this field [8–15], authors of this paper made an assumption that combining a cogeneration system on the basis of ICE and GHP with direct mechanical drive allows to significantly increase the efficiency of autonomous energy supply systems in the case of considerable season fluctuations in electricity and heating demands.

The analysis of fossil fuel consumption for a combined energy supply of standard building placed in different climatic zones with different methods of power, heat and cold generation, such as monogeneration (MG), cogeneration (CG), complex cogeneration (CCG) and trigeneration (TG) were provided in this paper.

2. Generalized technical features of the trigeneration plant

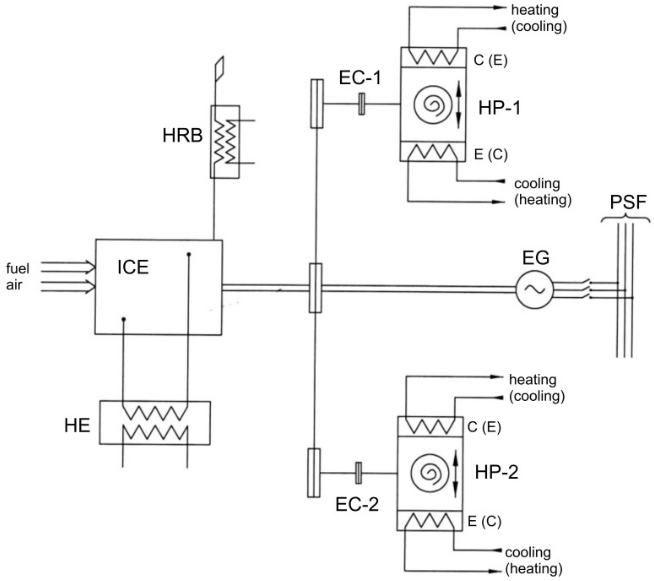
The concept of a trigeneration plant, including ICE with a heat utilization system and two reversible heat pumps with direct mechanical drive compressors is proposed by the authors in order to carry out the research. The experimental plant is based on this concept for physical modeling, in order to receiving initial data for the creation of a mathematical model and its calibration. The experimental plant allows simulation of real conditions for energy generation at any ratio of heat, cold and electricity generation.

Figure 1 shows the general structure of a trigeneration plant.

When electromagnetic couplers EC-1 and EC-2 are switched on, the ICE rotor's spinning is transferred to the heat pump compressors. The heat pumps contain 4 way valves, by which it is possible to reverse the heat flow directions; the condenser (C) becomes an evaporator (E) and vice versa.

Thermal energy generated by the ICE is discharged with exhaust gases and from the water jacket. Heat of the exhaust gases is recovered by the use of the boiler (HRB) (gas-water type). Removal of heat from the coolant is achieved by means of a water-cooled heat exchanger (HE).

Electricity from the tires of the electric generator is supplied to the consumer.



ICE – internal combustion engine, diesel or gas piston; HE – heat exchanger for energy recovery from engine water cooling system; HRB – heat recovery boiler (gas /water) of exhaust gases; HP-1 & HP-2 – reversible vapour compression heat pumps with direct (V-belt) mechanical drive from ICE; C – condenser; E – evaporator; EG – electric generator; EC – electromagnetic coupling; PSF – power supply feeder.

Fig. 1. Generalized technical structure of the trigeneration plant (TGP).

2.1 Monogenertion of the electricity by the TGP. Mode "MG"

Figure 2 (a) shows the configuration of the TGP when set up for simple monogeneration.

In this mode the plant only generates electrical energy. In this case the exhaust gases can be discharged into the atmosphere without cooling through the bypass or they can be cooled in a heat recovery boiler using the collected heat for regenerating the geothermal collector (GC).

In order to configure the TGP for the monogeneration mode, the following operations are carried out:

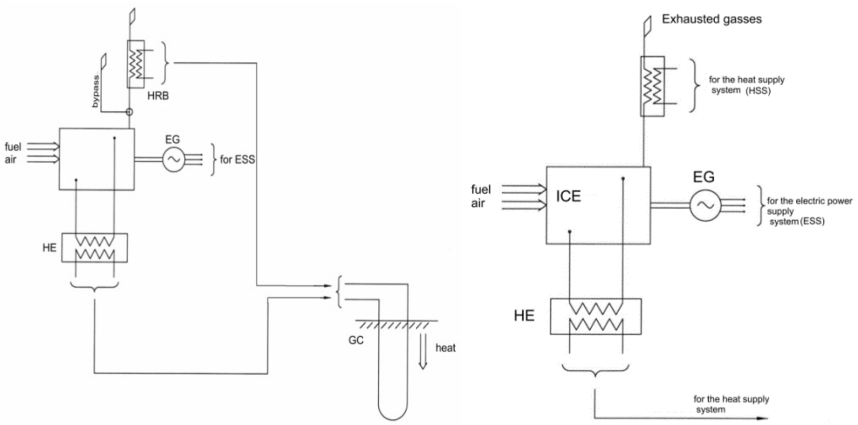
- The electric couplings to the heat pumps are disconnected;
- The heat recovery boiler (HRB) and the water jacket heat exchanger (HE) are connected to the geothermal collector (GC);
- The electrical load is connected to the generator.

2.2 Simple cogeneration of electrical and heat power by the TGP in cogeneration mode (CG)

Figure 2 (b) shows how the TGP can be set up for the cogeneration of both heat and electricity. The plant produces electrical power in the quantity required and the heat produced by the ICE (some losses into the environment cannot be recovered), is recovered from the water jacket by means of the heat recovery boiler and heat exchanger. Extracted heat is used for heating, hot water supply and technological needs.

In order to configure the TGP to a simple cogeneration mode:

- The heat pumps are disconnected;
- The heat recovery boiler (HRB) on the secondary side is connected to the heating system;
- The water jacket heat exchanger (HE) on the secondary side is connected to the heating system;
- The electrical load is connected to the generator.



(a) (b)

Fig. 2. (a) Configuration of the TGP set up in "Monogeneration Mode" (heat and cooling loads missing); (b) Configuration of the TGP in "Cogeneration Mode", "CG".

2.3 Cogeneration of electrical and heat energies with a geothermal heat pump. Mode "CCG"

The plant produces electric energy as demanded and the heat formed by the ICE (excluding irrecoverable losses) is utilized in the heating system (as in the simple cogeneration configuration).

Complex cogeneration (Figure 3 (a)), where it is assumed that the amount of mechanical energy extracted to generate electrical energy is less than the maximum engine power and part of the mechanical energy is consumed in driving heat pump compressors (one or two in parallel operation). The heat pump evaporator is in a hydraulic circuit with the geo-collector and the condenser side of the heat pump recovers heat to transfer to the heating system.

In order to configure the TGP to operate in complex cogeneration mode, the following operations are carried out:

- The electromagnetic coupling to the heat pumps are connected;
- 4 way valves are opened to the heat pumps to direct low-grade heat from the geo-collector and transmit heat to the heating system;
- Heat exchangers HRB, HE and a heat pump condenser are included in the heating system;
- The electrical load is connected to the generator.

2.4 Trigeneration. Simultaneous production of electricity, heat and cold. Mode "TG"

A necessity of TG configuration arises in cases when you need simultaneous generation of electricity, heat and cold (e.g. for cooling).

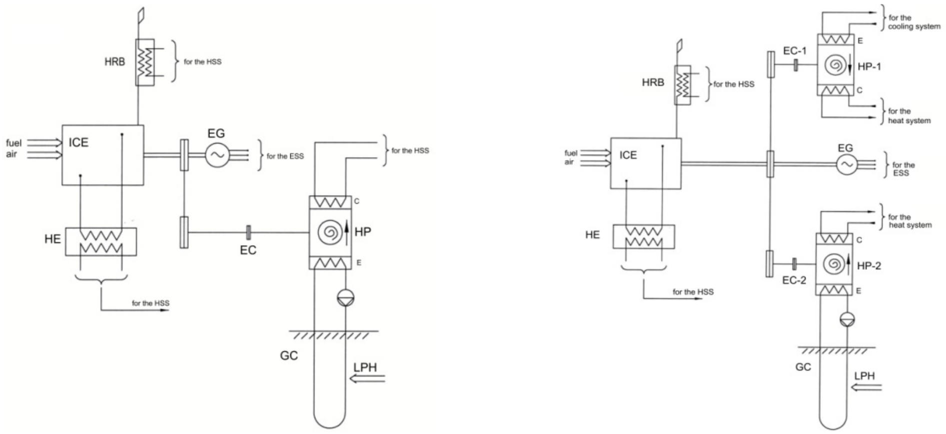
Figure 3 (b), shows the configuration of the TGP for trigeneration. The plant produces electrical energy for consumption and the heat formed in the ICE (less irrecoverable losses) is used in the heating system as in the “CG”, “CCG” modes.

When the TGP works in a trigeneration scheme, several heat flows are removing into the heating system. These include: waste heat from the ICE, heat removing from the heat pump condenser HP-1 and heat obtained from heat pump HP- 2 from a low-grade heat source (the geo-collector).

In order to convert the TGP to a trigeneration mode, the following operations are carried out:

- The electromagnetic coupling to the heat pumps are connected;
- Heat pump HP-1 4 way valve is switched to direct heat removing from the cooling facility into the heating system;
- Heat pump HP-2 4 way valve is switched to direct low-grade heat removing from the geo-collector into the heating system;

- Heat exchangers HRB, HE and heat pumps condensers HP-1 and HP-2 are included in the heating system;
- The electrical load is connected to the generator.



(a) (b)

Fig. 3. (a) Configuration of the TGP in "Complex Cogeneration Mode" ("CCG") (simultaneous production of electrical and heat power using an ICE and heat pump); (b) Configuration of the TGP in "Trigeneration" ("TG") mode (simultaneous production of electricity, heat and cold).

3. Results

The climate of Kazakhstan is sharply continental with pronounced differences between the natural geographic zones [16]. For the country as a whole there are large fluctuations in temperature both daily and annually. In the plains and lowlands the annual and monthly temperatures vary from north to south. The average air temperature throughout the plain and lowland part of the country is positive. In the north it is +0.4 °C, in southernmost regions it reaches +13.7 °C. In mountainous areas the average temperature drops with altitude. The coldest months in Kazakhstan are January and February. The average temperature in the north is -19.7 °C and in the south -1.5 °C. In the north temperatures can sometimes reach -54 °C, while in the south the temperature rarely drops below -30 °C. The warmest month in Kazakhstan is July with average temperatures in the north of +18.8 °C and in the south +28.8 ° C. The highest temperature in the north does not exceed +41 °C and in the south +47 °C [17].

For the purposes of analysis, the country is divided into temperature zones based on the number of degree.days of heating in the region. The degree.day is an indicator obtained by evaluating the difference between the air temperature inside the heated premise and the average outdoor temperature during the heating period and then multiplying it by the duration of the heating period. The heating period is defined as the number of days with an average temperature below 8 °C (in accordance with national standard CNR of RK 2.04-21-2004). This results in the following five zones (Figure 4):

- ***Zone I*** (2000–3000 degree.days) - the territory of the south-western and southern Kazakhstan, with an average temperature during the heating period of 1.4°C. Major cities in the zone – Shymkent and Aktau;
- ***Zone II*** (3000–4000 degree.days) – most of southern Kazakhstan not in Zone I as far as Almaty to the east, with an average temperature during the heating period between –0.6 °C and –8.5 °C. Major cities within the zone are Kyzylorda, Turkestan, Taraz and Almaty;
- ***Zone III*** (4000–5000 degree.days) - the territory of central Kazakhstan, with an average temperature during the heating period within the limits –3.5 °C to –6.5 °C. Major cities within the zone are Aralsk, Atyrau and Taldykurgan;
- ***Zone IV*** (5000–6000 degree.days) – northern central Kazakhstan, with an average temperature during the heating period within the limits of –6.5 and –8.5 °C. Major cities in the zone are Aktobe, Uralsk, Oskemen and Torgay;

Zone V (6000-7000 degree.days) - the territory of the northern Kazakhstan, with an average temperature during the heating period between –7.5 and –12 °C. Major cities in this zone include Astana, Pavlodar, Petropavlosk, Kostanay and Kokshetau.

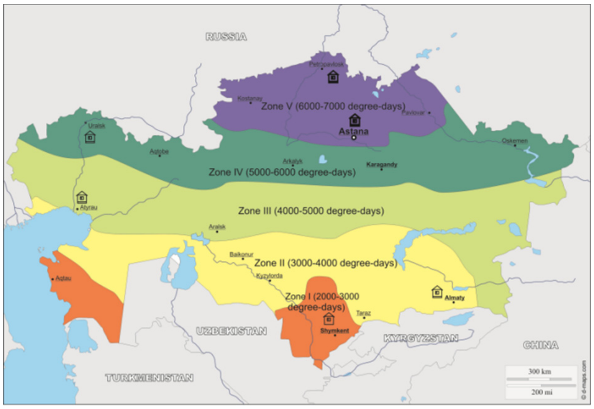


Fig. 4. Temperature zones of the RK (the house icons mark the positions of the "standard buildings").

The average monthly temperatures of these zones are illustrated in Figure 5 (a).

In order to compare the energy efficiencies of complex energy supply systems for residential properties located in different climatic zones of Kazakhstan, a model "standard building" of 150 m^2 was proposed, with a baseline heating rate of 0.0375 kWh / (m2×°C×day). Electrical energy consumption was set to ensure a comfortable stay by the assumption of 120 kWh per person per month. In the "standard building" 5 people are assumed to reside and the maximum energy consumption for domestic hot water is taken to be 230 kWh per person per month. Calculations of energy consumption in a "standard building" were made for the 5 temperature zones (Figure 5 (b)).

The energy efficiencies of various types of power generation were modelled using special software developed using LabView [18]. The initial data used for the calculations were annual and daily load diagrams.

The program models annual and daily loads for the four different modes of power supply:

- Monogeneration (MG); the separate generation of electricity in a diesel (gas piston) generator (DG/GG) and heat in a boiler;
- Cogeneration (CG); a combined generation of heat and power energy with a diesel (gas piston) generator with an additional boiler;
- Complex cogeneration (CCG); the combined generation of heat and power energy using a diesel (gas piston) generator with an integrated heat pump plant;
- Trigeneration (TG); production of all types of energy in a single plant.

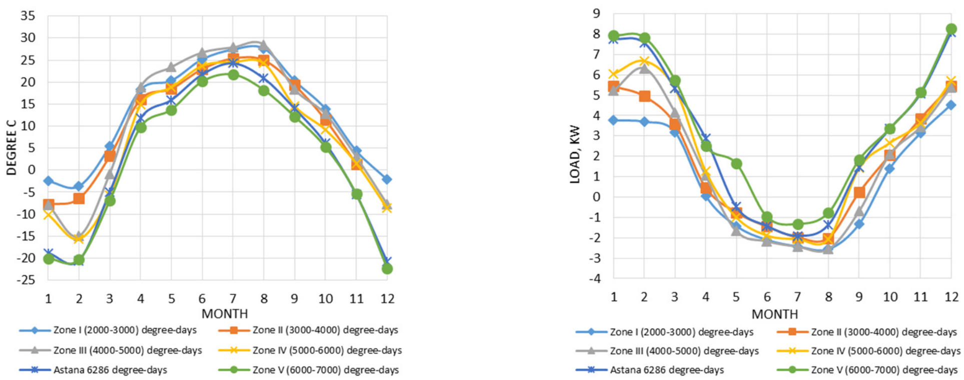


Fig. 5. (a) Average monthly temperatures for selected zones of the RK; (b) Heating system and air conditioning consumptions over a year for the 5 temperature zones of the RK.

Figure 6 shows the fuel consumption data for the trigeneration plant in four modes in three climatic zones (I, III & V).

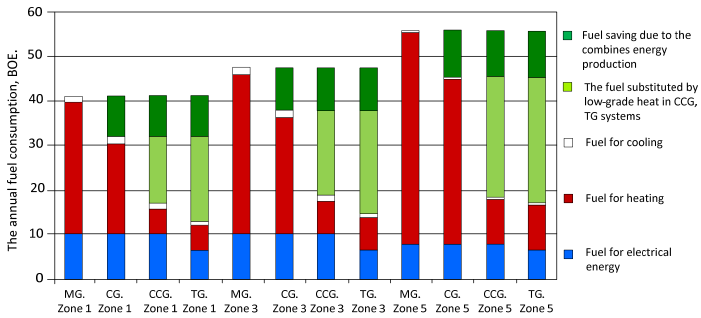


Fig. 6. Annual fuel consumption figures for the generation of various types of energy.

The program consists of two main sections:

- Analysis of annual loads. Allows the computation of the required capacity of backbone units, depending on the power supply circuit (see Table 1), to determine the energy performance of the system, the annual fuel consumption;
- Analysis of the daily loads. Allows to define capacity of heat storage and electrical batteries.

Calculations were carried out for 150 m^2 "standard buildings" located in the five temperature zones. Fuel consumption calculations (Table 2) were carried out for each temperature zone and for the different types of energy supply (normalized to a barrel of oil equivalent (BOE)).

Table 1. Components assumed for each aggregate generation system.

	MG	CG	CCG	TG
Electric power supply	DG/GG	DG/GG	DG/GG	DG/GG
Heat power supply	Boiler	ICE Cooling System +Boiler	ICE Cooling System +GHP	ICE Cooling System +GHP
Cooling	Conditioner (as additional electrical load)	Conditioner (as additional electrical load)	Conditioner (as additional electrical load)	GHP

Table 2. Annual fuel consumptions in the geographic zones (BOE).

	Zone I (BOE)	Zone II (BOE)	Zone III (BOE)	Zone IV (BOE)	Astana (BOE)	Zone V (BOE)
MG	41,12	44,57	47,42	50,14	55,96	55,71
CG	31,92	35,04	37,81	40,26	45,63	45,32
CCG	17,23	16,99	18,9	18,65	19,33	18,4
TG	13,04	14,04	14,65	15,45	17,03	17,05

4. Conclusion

The energy savings achieved by the application of cogeneration plants to residential buildings in regions having significant seasonal temperature variations is complex and does not necessarily lead to the expected economic effects. Annual reductions in fuel consumption are less than 22 % for the "warm" climate zones of Kazakhstan and 19 % for the "cold" regions.

The use of a trigeneration plant as the main energy source in autonomous systems can result in a threefold or more reduction in fossil fuel consumption when compared to monogeneration. This applies to all the investigated temperature zones in Kazakhstan, and is accompanied by reduced greenhouse gas emissions.

Fuel saving is achieved by combining generation with the recovery of low-grade heat from the Earth's crust. Energy losses are reduced by the use of heat pumps to generate cold for air conditioning. We expect that additional energy savings can be achieved by the use of natural air-conditioning with a simultaneous seasonal regeneration of a geothermal-collector.

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